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COMPUTER SCIENCE AND AUTOMATION

COMPUTER SCIENCE MEETS AUTOMATION

VOLUME I

Session 1 - Systems Engineering and Intelligent Systems

Session 2 - Advances in Control Theory and Control Engineering

Session 3 - Optimisation and Management of Complex Systems and Networked Systems

Session 4 - Intelligent Vehicles and Mobile Systems

Session 5 - Robotics and Motion Systems

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Preface

Dear Participants,

Confronted with the ever-increasing complexity of technical processes and the growing demands on their efficiency, security and flexibility, the scientific world needs to establish new methods of engineering design and new methods of systems operation. The factors likely to affect the design of the smart systems of the future will doubtless include the following:

- As computational costs decrease, it will be possible to apply more complex algorithms, even in real time. These algorithms will take into account system nonlinearities or provide online optimisation of the system's performance.
- New fields of application will be addressed. Interest is now being expressed, beyond that in "classical" technical systems and processes, in environmental systems or medical and bioengineering applications.
- The boundaries between software and hardware design are being eroded. New design methods will include co-design of software and hardware and even of sensor and actuator components.
- Automation will not only replace human operators but will assist, support and supervise humans so that their work is safe and even more effective.
- Networked systems or swarms will be crucial, requiring improvement of the communication within them and study of how their behaviour can be made globally consistent.
- The issues of security and safety, not only during the operation of systems but also in the course of their design, will continue to increase in importance.

The title "Computer Science meets Automation", borne by the 52nd International Scientific Colloquium (IWK) at the Technische Universität Ilmenau, Germany, expresses the desire of scientists and engineers to rise to these challenges, cooperating closely on innovative methods in the two disciplines of computer science and automation.

The IWK has a long tradition going back as far as 1953. In the years before 1989, a major function of the colloquium was to bring together scientists from both sides of the Iron Curtain. Naturally, bonds were also deepened between the countries from the East. Today, the objective of the colloquium is still to bring researchers together. They come from the eastern and western member states of the European Union, and, indeed, from all over the world. All who wish to share their ideas on the points where "Computer Science meets Automation" are addressed by this colloquium at the Technische Universität Ilmenau.

All the University's Faculties have joined forces to ensure that nothing is left out. Control engineering, information science, cybernetics, communication technology and systems engineering – for all of these and their applications (ranging from biological systems to heavy engineering), the issues are being covered.

Together with all the organizers I should like to thank you for your contributions to the conference, ensuring, as they do, a most interesting colloquium programme of an interdisciplinary nature.
I am looking forward to an inspiring colloquium. It promises to be a fine platform for you to present your research, to address new concepts and to meet colleagues in Ilmenau.

Professor Peter Scharff
Rector, TU Ilmenau

Professor Christoph Ament
Head of Organisation

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52nd Internationales Wissenschaftliches Kolloquium
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10 – 13 September 2007

Arvid Amthor / Tino Hausotte / Gerd Jäger / Pu Li

Friction Modeling on Nanometerscale and Experimental Verification

Abstract

This work concerns the modeling and experimental verification of the extremly non-linear friction behavior in positionning on nanometerscale. The main target of this work is to adjust and identify a simple dynamic friction model which allows a model-based estimation of the friction force in combination with the system inertia against displacement. Experiments in the pre-sliding and sliding friction regimes are conducted on an experimental setup. A hybrid two-stage parameter estimation algorithm is proposed to fit the model parameters based on the experimental data.

I. INTRODUCTION

Friction is a highly nonlinear phenomenon which is present in nearly all mechanical systems. It is induced by interactions between the two rubbing surfaces and depends on several parameters such as surface topography, surface materials or lubricant. Friction can be differentiated into two regimes: the presliding (micro-slip) and the sliding (gross sliding) regime. In the first regime adhesive forces are dominant and friction behaves like a nonlinear spring. In the sliding regime the contacts between the asperities are broken and the friction force depends on the shearing resistance of these asperities. The transition between the mentioned two regimes is continuous and depends on many effects like moving direction, rate of the applied force and others. During a controlled motion these non-linear characteristics lead to tracking errors, limit cycles, stick-slip motion and so on [2]. Due to this dominant nonlinear impact on movements with small displacements, modeling friction is essential to achieve a high-precision dynamic positioning. This is a quite challenging task, since accurate friction modeling based on physical principles and material/surface properties is not possible to date. Hence "Greybox" and "Blackbox" models in combination with efficient identification methods based upon experimentally observed data are often used to solve this problem [1].

II. MECHANICAL SYSTEM WITH FRICTION

A simple mechanical system with friction is considered (Fig.1) [7], [8]. It consists of a mass m, a linear spring k and a damper c. The system is stimulated by a force u and the (unmeasureable) friction force f resist the excited motion.

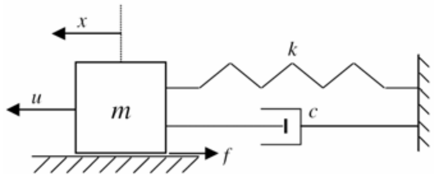

Fig. 1: Simple mechanical system with friction

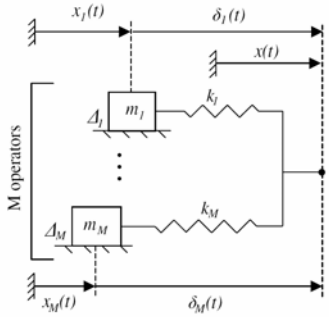

Fig. 2: Basic Maxwell-Slip model structure

This simple mechanical system can be modeled as:

$$m \cdot a + c \cdot v + k \cdot x = u - f \tag{1}$$

The acceleration $a(t)$ and the velocity $v(t)$ are typically obtained by numerical differentiation and this lead to numerical errors and phase shift. The basic idea is that these signals can be calculated via a moving average representation of the order n_v and n_a respectively:

$$v(t) \approx \sum_{j=0}^{n_v} p_j \cdot x(t-j) \tag{2}$$

$$a(t) \approx \sum_{j=0}^{n_a} q_j \cdot x(t-j) \tag{3}$$

A various number of dynamic friction models are available and in this case an extended version of the basic Maxwell-Slip model structure is chosen [1]. This so called Generalized Maxwell-Slip friction model is selected because it is simple and able to predict the friction force with a high accuracy. Furthermore, it can reflect friction phenomenons like the presliding hysteresis with nonlocal memory. This model consists of M elasto-slide operators in a parallel configuration (Fig. 2). Each operator has a negligible mass and a maximal spring deformation (treshold) Δi. All elements are subjected to an equal displacement $x(t)$. Hence the Maxwell-Slip structure can be modeled by a set of nonlinear state equations [5], [6]:

$$\delta_i(t+1) = \mathrm{sgn}[x(t+1) - x(t) + \delta_i(t)] \cdot \min\{|x(t+1) - x(t) + \delta_i(t)|, \Delta_i\};\ i = 1 \dots M \tag{4}$$

The friction force can be approximated by summing up the spring force of each operator:

$$f(t) = \sum_{i=0}^{M} k_i \cdot \delta_i(t) \ with \ t = 1, 2, \ldots \ reffering \ to \ discrete \ time \tag{5}$$

According to [7], [8] it is possible to allow the friction force depending upon present and past values of the spring deflection, as well as upon values of the displacement. This can be achieved by calculating the friction force by using Finite Impulse Response (FIR) filters of order n' and n respectively:

$$f(t) = \sum_{j=0}^{n'} r_j \cdot x(t-j) + \sum_{j=0}^{n} \theta_j^T \cdot \delta(t-j) \ with \ \delta(t) = [\delta_1(t) \ldots \delta_M(t)]^T \tag{6}$$

The displacement filter has one dimension and the deflection filter M dimensions. r_j and θ_j^T are the vector coefficients of the FIR filters. Equations (2), (3) and (6) represent approximations of acceleration, velocity and friction force based on the past displacements. Placing of these expressions into equation (1) leads to a time discrete system model:

$$\begin{aligned} m \cdot \left(\sum_{j=0}^{n_a} q_j \cdot x(t-j) \right) + c \cdot \left(\sum_{j=0}^{n_v} p_j \cdot x(t-j) \right) + k \cdot x(t) = \\ u(t) - \sum_{j=0}^{n'} r_j \cdot x(t-j) - \sum_{j=0}^{n} \theta_j^T \cdot \delta(t-j) \end{aligned} \tag{7}$$

which can be rewritten as:

$$u(t) = \sum_{j=0}^{n_x} g_j \cdot x(t-j) + \sum_{j=0}^{n} \theta_j^T \cdot \delta(t-j) \tag{8}$$

$$\begin{aligned} with: \quad & n_x = \max\{n_a, n_v, n'\} \\ & g_j = m \cdot q_j + c \cdot p_j + k + r_j \end{aligned}$$

This so called DNLRX (*Dynamic NonLinear Regression with direct application of eXcitation*) model consists of two finite impulse response filters. It can provide the current value of the applied force from the known displacement history. In addition, the DNLRX model reflects the *inverse* system behavior of the considered mechanical system. Thus it can be used in a model-based feedforward control system to compensate the disturbances introduced by the non-linear friction characteristics.

III. PARAMETER ESTIMATION ALGORITHM

The parameter identification algorithm uses pairs of displacement - applied force signals to determine the model parameters via a quadratic cost function:

$$J = \sum_{t=k}^{N} e^2(t) \tag{9}$$

$e^2(t)$ is calculated as difference between the measured, $\hat{u}(t)$, and the model provided, $u(t)$, friction:

$$e(t) = \hat{u}(t) - u(t) \tag{10}$$

Substituting equation (8) in equation (10) yields:

$$\hat{u}(t) = \theta^T \cdot \left[x(t) \ \ldots \ x(t-n_x) \ \vdots \ \delta^T(t) \ \ldots \ \delta^T(t-n) \ \vdots \ 1 \right]^T + \ e(t) \tag{11}$$

$$with: \ \theta = \left[g_0 \ \ldots \ g_{n_x} \ \vdots \ \theta_0^T \ \ldots \theta_n^T \ \vdots \ b \right]^T; \ (\text{b}-Offset)$$

where θ and the threshold-vector $d = [\Delta_1 \ \ldots \ \Delta_M]$ are the parameters that will be identified. The model is nonlinear with respect to d and linear with respect to θ. A sequential two-stage optimization algorithm is used to identify the model parameters, i.e.

$$[d \ \theta] = \arg\min_{d} \left\{ \min_{\theta} J(\theta, d) \right\} \tag{12}$$

At the first stage a genetic algorithm is utilized to find the areas of local minimas in the parameter space [3]. At the second stage the Nelder-Mead-Simplex algorithm is used to locate the global minimum in the regions provided in the first stage [9]. For initialization of the proposed identification algorithm, initial values for the maximum deflection thresholds of the springs (Δ_i) are required. To find these initial values, a data-pair is selected where the system is in sliding regime. At this moment (t_{sl}) all Maxwell-Slip elements are sliding and the assumption $\delta_i = \text{sgn}[x(t_{sl})] \cdot \Delta_i$ is justified.

To obtain an optimal identification result, the "dominant" displacement extremum of the time series is selected. For the identification process only data pairs with $t > t_{sl}$ are used. To determine the quality of identification, the *Normalized Output Error* is utilized:

$$NOE = \left(\frac{\sum_{t=k}^{N} (\hat{u}(t) - u(t))^2}{\sum_{t=k}^{N} (\hat{u}(t) - \hat{m_u})^2} \right) \cdot 100\% \tag{13}$$

where $\hat{m_u}$ is the sample mean of the current friction signal and k is specified in equation (9).

IV. EXPERIMENTAL SETUP

For experimental verification a linear guideway driven by a voice coil actuator is used. The operating range of this system is 25 mm. The friction is introduced to the system by the ball bearings of the guideway. The position is measured by a laser interferometer SP-2000 of the company SIOS with a resolution below 0.1 nm. For data aquisition and control purposes a modular dSpace© system in combination with Matlab/Simulink© is utilized. The position is sampled with a rate of 25 kHz and the control algorithm works with a sampling rate of 6.25 kHz. For more detailed information about the experimental setup the reader is referred to [4], [10].

V. RESULTS

The identification process starts with a selection of the optimal model order (M, n, n_x). This task can be done by evaluating the value of NOE. Table 1 shows the identification results of a given friction-displacement dataset with several model configurations. Due to the fact that the cost value decreases practically insignificant NOE beyond five Maxwell-Slip elements with a FIR filter length of three, this model order is most suitable to reflect the friction behaviour with respect to the computational cost. Based on this result the mentioned model order has been used for the following identification process.

model order	NOE
DNLRX(2,2,1)	0.3276 %
DNLRX(3,2,2)	0.1417 %
DNLRX(4,2,2)	0.1079 %
DNLRX(5,3,3)	0.0837 %
DNLRX(6,3,3)	0.0598 %
DNLRX(7,4,4)	0.0621 %

Table 1: NOE with respect to the model order (M,n,n_x)

Fig. 3 presents the identification dataset composed of the displacement (a) and the related applied force (b). The dataset consists of displacements in the sliding as well as in the presliding regime. The data was lowpass filtered with a cutoff frequency of 50 Hz. To speed up the identification process the algorithm was carried out only at every hundredth data-pair. In comparison with a identification using every data sample the performance did not degrade significantly (about 0.01%) and the computing time was reduced by a factor of 30. As shown in Fig. 3 (c), the NOE after the identification is below 0.083%. This demonstrate the effectiveness of the proposed two-stage identification algorithm to find a nearly global minimum in the parameter space. Fig. 4 shows the the ability of the identified model to predict the system behaviour for a different validation dataset. In that case the NOE is 1.33%. It should be mentioned that t_{sl} is the first sample of the plots in Fig. 3 and 4.

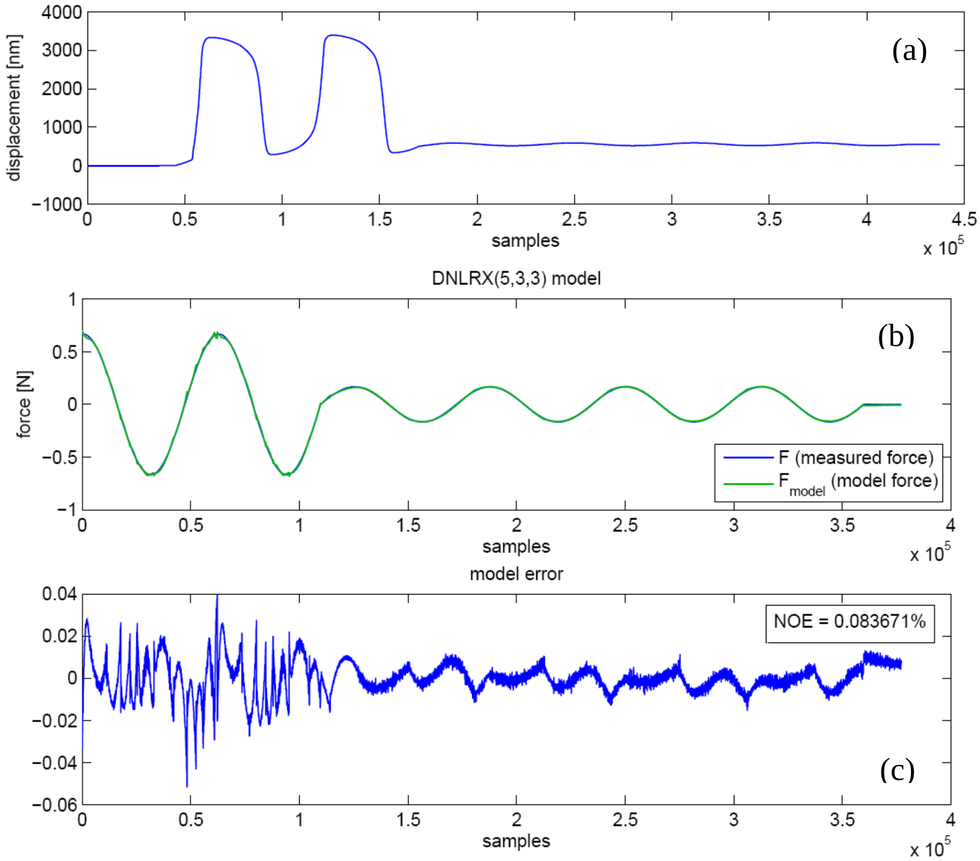

Fig. 3: Identification dataset: (a) displacement; (b) applied force; (c) model based error (NOE)

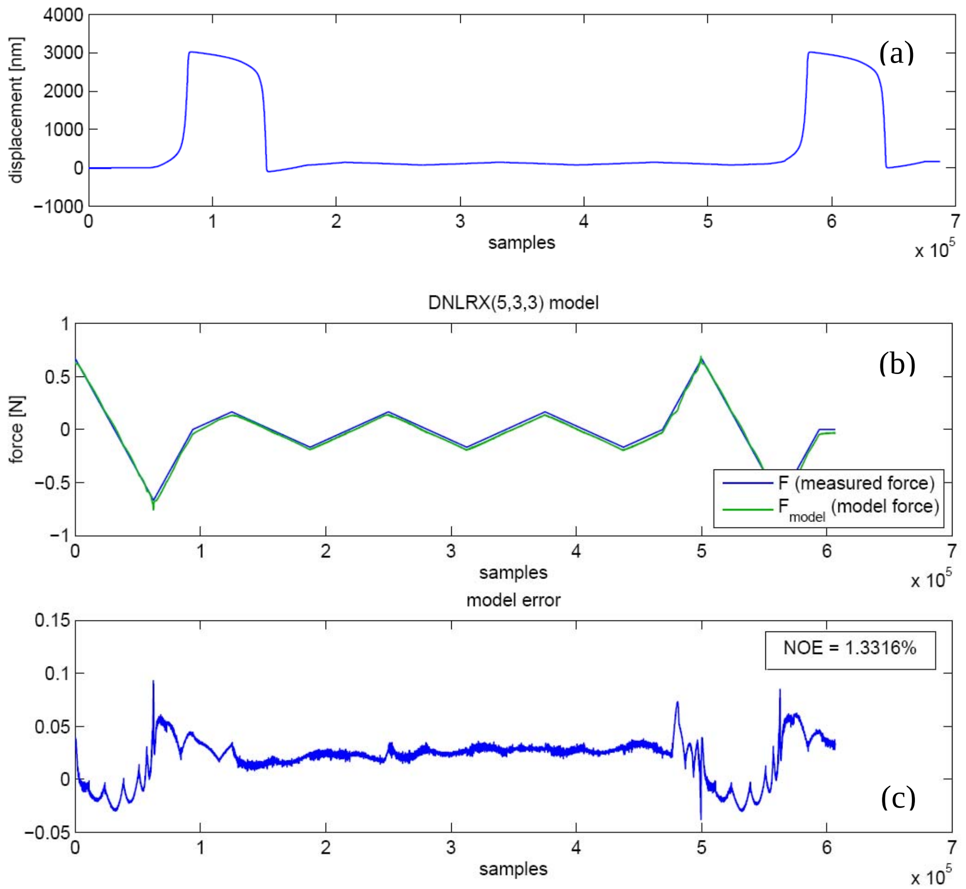

Fig. 4: Validation dataset: (a) displacement; (b) applied force; (c) model based error (NOE)

VI. CONCLUSION

The problem of dynamic friction modeling has been adressed in this work. A two-stage approach to parameter identification is proposed. One of the most commonly used friction models has been analyzed and identified with experimental data. It is shown that this so-called DNLRX model is able to reflect the friction behaviour of ball bearings on nanometerscale and thus can be used for positioning control.

VII. ACKNOWLEDGMENTS

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References:

[1] AL-BENDER, F. ; FASSOIS, D. G. ; PARLITZ, U. ; WORDEN, K.: Identification of Pre-Sliding and Sliding Friction Dynamics: Grey Box and Black Box Models. In: *Mechanical Systems and Signal Processing,* 2005

[2] ARMSTRONG-HÉOUVRY, B. ; DUPONT, P. ; DE WIT, C.: A survey of Models, Analysis Tools and Compensation Methods for Control of Machines with Friction. In: *Automatica, Vol. 30, No. 7*, 1994

[3] HOUK, CH. R. ; JOINES, J. A. ; KAY, M. G.: A Genetic Algorithm for Function Optimization: A Matlab Implementation http://www.ise.ncsu.edu/mirage/GAToolBox/gaot/. Version: 1998, Abruf: 8.06.2007

[4] HAUSOTTE, T.: *Nanopositionier- und Nanomessmaschine*, Technische Universität Ilmenau, Dissertation, 2002

[5] LAMPAERT, V. ; AL-BENDER, F. ; SWEVERS, J.: Modification of the Leuven Integrated Friction Model Structure. In: *IEEE Transactions on Automatic Control, Vol. 47, No. 4*, 2002

[6] LAMPAERT, V. ; AL-BENDER, F. ; SWEVERS, J.: A Generalized Maxwell-Slip Friction Model appropriate for Control Purposes. In: *IEEE International Conference for Physics and Control,* St. Petersburg, Russia, Proceedings, 2003

[7] RIZOS, D.D. ; FASSOIS, D.: Maxwell Slip Model Based Identification and Control of Systems with Friction, In: *44th IEEE Conference on Decision and Control, and the European Control Conference 2005,* Sevilla, Spanien, Proceedings, 2005

[8] RIZOS, D.D. ; FASSOIS, D.: Friction Identification based upon the LuGre and Maxwell Slip Models, In: *16th IFAC World Congress,* Prag, Proceedings, 2005

[9] WERNSTEDT, J.: Experimentelle Prozessanalyse. Berlin : Verlag Technik, 1989, S.201–206

[10] ZIMMERMANN, J. ; SAWODNY, O. ; HAUSOTTE, T. ; JÄGER, G.: Friction Modelling of a linear high-precision Actuator. In: *IFAC World Congress***,** Prag, Proceedings, 2005

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